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Rheology of Oil Films at High Contact Pressures

WE report here a new approach to studying the shear behaviour of thin films of oil under conditions of elastohydrodynamic lubrication such as arise at points of contact in ball bearings or between gear teeth. During its passage through the contact the oil is rapidly compressed to pressures in the region of 10^4 bar and then sheared by the sliding motion of the metal surfaces. Hitherto this behaviour has been studied using rolling contact disk machines in which rollers having parallel axes are pressed into contact. Rolling motion generates an oil film of known thickness ($\sim 1\ \mu m$) between the hard steel surfaces; superimposed sliding shears the film. At very small sliding speeds—shear rates—the behaviour is linear: the mean shear stress required to shear the film $\bar{\tau}$ is proportional to the sliding speed. At higher sliding speeds the mean shear stress reaches a maximum (critical) value $\bar{\tau}_c$[1]. It has been suggested[2] that the observed behaviour can be explained by the oil exhibiting viscoelastic properties at these high pressures, when the viscosity is known to increase by many orders of magnitude. Unfortunately this hypothesis cannot be tested with certainty by conventional disk machine tests, which do not distinguish unequivocally between viscous and elastic response of the fluid in the contact zone. We report here a different rolling

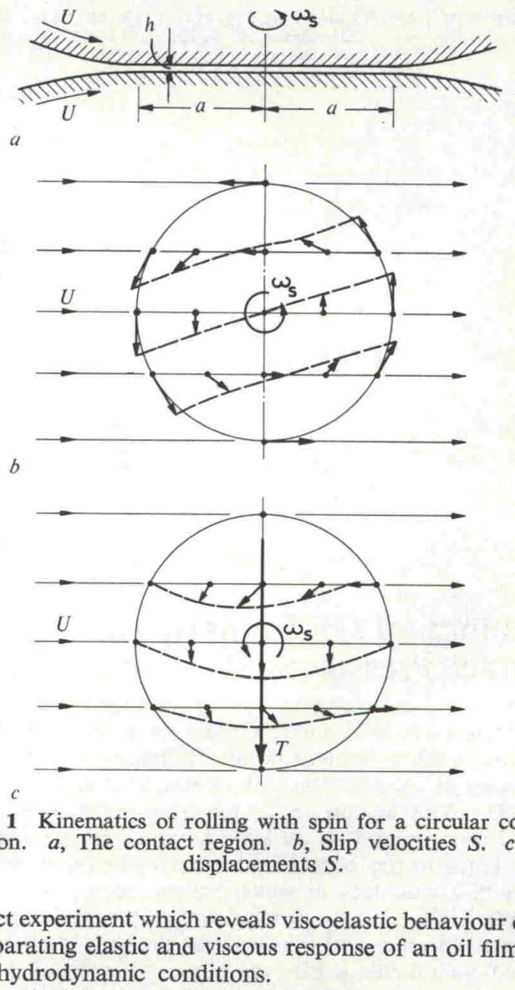

Fig. 1 Kinematics of rolling with spin for a circular contact region. *a*, The contact region. *b*, Slip velocities *S*. *c*, Slip displacements *S*.

contact experiment which reveals viscoelastic behaviour directly by separating elastic and viscous response of an oil film under elastohydrodynamic conditions.

The principle of the experiment is illustrated in Fig. 1. Two rollers having suitably curved profiles are pressed together by a force P such that, in the absence of lubricant, they would make contact over a circular area of radius a. They are rolled together with equal peripheral speeds U so that they generate an elastohydrodynamic film of thickness h. One surface is then given a small angular velocity of spin ω_s which shears the film as shown. Following a fluid element along any streamline through the "contact" region we see that it is sheared first in one direction and then in the other. This is the significant difference from the conventional disk machine experiment, in which the fluid is continually sheared in the same direction. A purely viscous fluid develops shear stresses in response to the shear rate vectors S (Fig. 1*b*). Clearly no net shear force will be exerted by the film in this case. An elastic film, on the other hand, will develop shear stresses in response to the total shear S experienced by the fluid elements. The total shear vectors are shown in 1*c*. Stresses developed in response to total shear give rise to a resultant force T acting perpendicular to the direction of rolling as shown. Thus a purely elastic film with constant shear modulus G would develop a shear stress GS/h. Integrating over the whole contact area gives

$$T=\frac{\pi}{4}\,\frac{Ga^4}{h}\,\frac{\omega}{U} \tag{1}$$

assuming that the solid surfaces do not deform in shear. In practice it is necessary to make a correction for the elastic deformation of the rollers.

The action of rolling combined with spin can be realized in several ways. We have used an apparatus designed by Poon and Haines[3], shown diagrammatically in Fig. 2. The (upper) crowned roller rolls in contact with the (lower) cylindrical roller. Spin is introduced by tilting the axis of rotation of the upper roller through an angle α in a vertical plane, thus introducing an angular velocity of spin, $\omega \sin \alpha$. The upper roller is mounted on a cantilever spring dynamometer to measure the transverse force T.

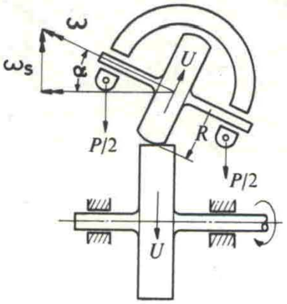

Fig. 2 Poon and Haines rolling contact apparatus. Angular velocity of spin, $\omega_s=\omega \sin\alpha$; peripheral rolling speed $U=\omega R$.

Exploratory tests have been made on two mineral oils: Shell Vitrea 79 (viscosity: 8.9 poise at 30° C), Shell Turbo 33 (0.84 poise at 30° C) and a synthetic fluid, di-2-ethyl hexyl phthalate (0.45 poise at 30° C). Evidence of elastic behaviour was found with all three fluids at high pressure. It was most marked for Vitrea 79 which has been tested in more detail.

Its response to shear appears to be almost completely elastic above a pressure of about 700 MN m^{-2} (10^5 lbf in^{-2}) and above a rolling speed of 0.4 m s^{-1}. The magnitude of the transverse force T is observed to increase with $\sin \alpha$, linearly at first and then reaching a maximum of about 0.03 poise when $\sin \alpha \simeq 20°$.

If the response is fully elastic then equation (1) can be used to deduce a value for the mean effective shear modulus $\bar{G}$ of the fluid for various test pressures and speeds. The results are shown in Fig. 3, where it appears that $\bar{G}$ has values in the range 10^2–10^3 MN m^{-2} which rise with pressure. The only independent measurements of the elastic modulus of lubricating fluids at high pressure have been made by Barlow *et al.*[4] and Hutton and Phillips[5] in which a pressurized sample of the fluid is subjected to high-frequency oscillatory shear. They find values of shear modulus which are about an order of magnitude higher than the values shown in Fig. 3. It must be borne in mind, however, that the fluids tested were different and that the pressure remains steady during the

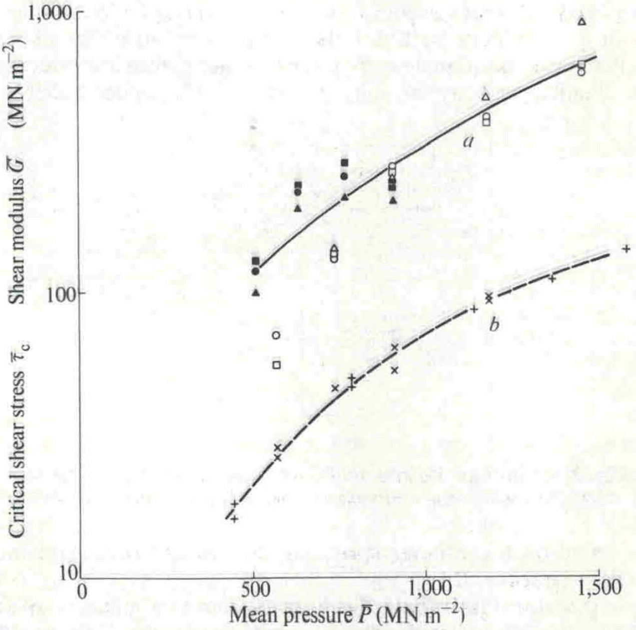

Fig. 3 *a*, Mean effective shear modulus $\bar{G}$ (Vitrea 79 at 25° C) deduced from rolling with spin experiments. $R=25$ mm : $U=0.40$ (○); 0.80 (□); 1.60 (△) m s^{-1}. $R=39$ mm : $U=0.40$ (●); 0.80 (■); 1.60 (▲) m s^{-1}. *b*, Mean critical shear stress $\bar{\tau}_c$ from Poon and Haines apparatus (×) and from disk machine (+).

oscillatory shear experiments, whereas it is very transitory (about 10^{-3} s) in the lubrication experiments.

In an earlier paper[1] it was suggested that the maximum shear stress observed in lubricated sliding might be due to shearing of the film in the manner of a plastic solid rather than a viscous liquid, when the shear stress reaches a critical mean value $\bar{\tau}_c$. This hypothesis seems even more probable if the film is behaving like an elastic solid at small strains. Values of $\bar{\tau}_c$ for Vitrea 79, obtained both in the disk machine and in the new apparatus, are also shown in Fig. 3. It will be seen that $\bar{\tau}_c \sim 0.2\ \bar{G}$. It is striking that a similar proportional relationship between yield stress and elastic modulus is commonly found to hold for glassy polymers[6].

We conclude from our new experiment that when a film of high viscosity mineral oil is subjected to small shearing strains under high pressure it exhibits "elastic" behaviour. At larger strains it is suggested that the film shears by a process of plastic flow.

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